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Patterns in ultra-high energy cosmic ray arrival directions: A possible footprint of large scale cosmic structures

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Abstract: The public available data of cosmic ray arrival directions with energies above 4×10^{19} eV present a broad maximum in the cumulative two-point autocorrelation function around 25°. This has been interpreted as the first imprint of the filamentary pattern of large scale structures (LSS) of matter in the near universe. We analyze this suggestion in light of the clustering properties expected from the PSCz catalogue of galaxies. The chance probability of the signal is consistent within $2\,\sigma$ with the predictions based on the catalogue. No evidence for a cross-correlation of the observed events with known overdensities in the LSS is found, which may be due to the role of the galactic and extragalactic magnetic fields, and is consistent with the limited statistics. The larger statistics to be collected by the Pierre Auger Observatory is needed to answer definitely the question.

1. Introduction

Above $\sim 10^{18} - 10^{19}$ eV (ultra-high energy cosmic rays, UHECRs) the rigidity of cosmic rays of galactic origin is high enough that the deflection in the galactic magnetic field (GMF) should not completely wash out correlations between their arrival directions and the galactic plane. The lack of any correlation down to the percent level and the difficulty to find suitable galactic candidates for acceleration up to $\sim 3 \times 10^{20}$ eV suggest an extragalactic origin for UHECRs. This hypothesis immediately raises the possibility that UHECRs may be messengers from deep space, and thus potential tracers of cosmic structures. Vice versa, one may exploit the present knowledge of the universe to infer some information on UHECR properties. In the following we summarize the anisotropies expected for extragalactic cosmic rays, while devoting Sec. 2 to treat more extensively the claim [1] of middle-scale clustering in the UHECR arrival directions.

i) Small scale clustering.
At energies high enough that deflections in extragalactic and galactic magnetic fields are sufficiently small, point sources may reveal themselves as small-scale clusters of UHECR arrival directions. This also requires a rather low density of UHECR sources so that the probability to observe several events of at least a subset of especially bright sources is large enough. We shall not review here the numerous studies that have been performed on this scenario especially after the AGASA claim of a statistically significant clustering of events [2]; unfortunately, other experiments with comparable or larger statistics have not yet confirmed this claim [3, 4].

ii) Anisotropies on medium-large scales.
Moving to lower energies, the energy-loss horizon of UHECRs and thereby the number of visible sources increases. Also, the number of potential accelerators should increase. Finally, deflections in magnetic fields become more important. As a result, the identification of single sources is challenging if not impossible. However, if UHECR sources trace to some degree the inhomogeneous distribution of matter revealed by the observed large scale structure (LSS) surveys within a few hundreds Mpc, some anisotropies on medium-large scales should be detectable. In [5] it was evaluated the expected anisotropy in the UHECR arrival distribution starting from the IRAS PSCz astronomical catalogue of nearby galaxies, taking into account the main selection effects in the catalogue as well as UHECR propagation effects. The con-

clusion was that about $300 - 400$ events at $E \gtrsim 4-5\times10^{19}$ eV are needed to confirm this scenario, a statistics which should be attained by the Auger experiment within a decade. Yet, by combining the $\mathcal{O}(100)$ events at $E \gtrsim 4-5\times10^{19}$ eV already collected by the previous generation of instruments, the authors of [1] found some evidence of a broad maximum of the cumulative two-point autocorrelation function of UHECR arrival directions around $25°$. The authors suggested that, given the energy dependence of the signal and its angular scale, it might be interpreted as a first signature of the large-scale structure of UHECR sources and of intervening magnetic fields. Recently, this claim was analyzed on the basis of sky maps derived from the PSCz catalogue [6]. The results are summarized in Sec. 2.

iii) Proper motion dipole (Compton-Getting effect.)
At even lower energies, also the LSS structure of sources disappears, both because the inhomogeneities in the source distribution will be averaged out due to the increased energy-loss horizon of UHECRs and because of deflections in the extra-galactic magnetic fields. Thus, if the Earth were in the cosmological rest frame the CR sky would appear isotropic. The observation of the cosmic microwave background (CMB) dipole clearly shows that this is not the case, and a dipole anisotropy of 0.6% in the cosmic ray intensity is expected if the CR flux is dominated by sources at cosmological distance. The shift of the dipole as function of energy provides information about the mean charge of CRs and the GMF. A 3 σ detection of this effect requires around 10^6 events in the considered energy range and is thus challenging but not impossible by the end of the lifetime of present detectors, at least at energies around 10^{18} eV. A similar effect also allows one to constrain the fraction of the diffuse gamma-ray background emitted by sources at cosmological distance, with promising detection possibilities for the GLAST satellite [7]. For possible relevance to indirect dark matter annihilation signatures, see [8].

iv) Rigidity effect due to the GMF.
Finally, if the extragalactic flux is still the dominant component at sufficiently low energy, the GMF may introduce blind regions on the external sky, which translate into observable anisotropies for an Earth-based observer, even if the UHECR flux is isotropic at the boundary of the Milky Way. Although the details depend on the GMF model, anisotropies of this kind may be expected in scenarios invoking a dominant extragalactic proton component already at $E \sim 4\times10^{17}$ eV or extragalactic iron nuclei at $E < 10^{19}$ eV [9].

2. UHECR clustering on medium scales and LSS

In our analysis, we closely follow the approach reported in [1], using a similar dataset extracted from available publications or talks of the AGASA, Yakutsk, SUGAR, and HiRes collaborations, opportunely rescaled in energy *a priori* to match the ankle dip (see [1] for details). We define the (cumulative) autocorrelation function w as a function of the separation angle δ as

$$w(\delta) = \sum_{i=2}^{N}\sum_{j=1}^{i-1}\Theta(\delta-\delta_{ij}), \tag{1}$$

where Θ is the step function, N the number of CRs considered and

$$\delta_{ij} = \cos^{-1}[\cos\rho_i\cos\rho_j+\sin\rho_i\sin\rho_j\cos(\phi_i-\phi_j)]$$

is the angular distance between the two cosmic rays i and j with coordinates (ρ,ϕ) on the sphere. We perform a large number $M \simeq 10^5$ of Monte Carlo simulations of N data sampled from a uniform distribution on the sky and for each realization j we calculate the autocorrelation function $w_j^{\rm iso}(\delta)$. The sets of random data match the number of data for the different experiments passing the cuts after rescaling, and are spatially distributed according to the exposures of the experiments. The formal probability $P(\delta)$ to observe an equal or larger value of the autocorrelation function by chance is

$$P(\delta) = \frac{1}{M}\sum_{j=1}^{M}\Theta[w_j^{\rm iso}(\delta) - w_\star(\delta)], \tag{2}$$

where $w_\star(\delta)$ is the observed value for the cosmic ray dataset and the convention $\Theta(0) = 1$ is being used. Relatively high values of P *and* $1-P$ indicate that the data are consistent with the null

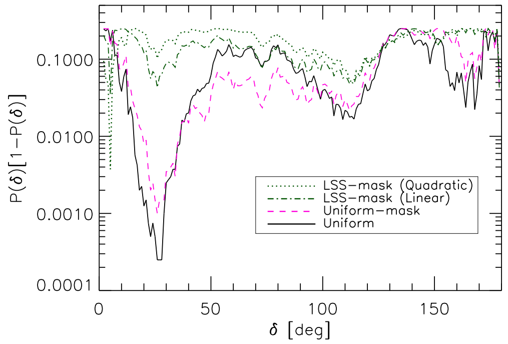

Figure 1: Chance probability $P(\delta)$ as defined in Eq. (2) for the combination of experimental data of Hires+AGASA+Yakutsk+SUGAR (solid line). The dashed purple line shows the same signal, when cosmic rays falling in the PSCz catalogue mask are disregarded. The dot-dashed green line is the same quantity, if the random events are sampled according to the LSS distribution, instead of a uniform one. The dotted green line is the result for a sample proportional to the square of the LSS distribution.

hypothesis being used to generate the comparison samples, while low values of P *or* $1-P$ indicate that the model is inappropriate to explain the data. Figure 1 summarizes our main results. The solid, black curve shows that under the same assumptions of Ref. [1], we obtain the same behavior for the function $P(\delta)$ (compare with their Fig. 5). To proceed further, we have to compare the previous signature with the one expected from a model of the LSS. As in [5], we use the IRAS PSCz galaxy catalogue [10]. We address to our previous work [5] as well as to the original paper [10] for technical details about the catalogue and about the calculation of the UHECR sky map—which takes into account energy losses as well—that we use in the following. It is important reminding that the catalogue suffers of an incomplete sky coverage.The unmapped regions are excluded from our analysis with the use of the binary mask available with the PSCz catalogue itself. This reduces the available sample by about 10% and the nominal chance probability to 0.1% (Fig. 1, dashed–purple line). The green/dot–dashed line in Fig. 1 shows the chance probability of the signature found in [1], if the random events are sampled according to the LSS distribution (obviously convolved with the experimental exposures), rather than from a uniform one. Finally, the dotted line shows the same result if the random events are sampled according to *the square* of the LSS distribution, as one would expect e.g. for a strongly biased population of sources. The prominent minimum of [1] is greatly reduced when using as null hypothesis the LSS model instead of the uniform one; this effect is even more prominent in the quadratic map. Also, the data are less clustered than expected from a uniform distribution at $\delta \sim 160°$, where $P \sim 1$. This additional puzzling feature disappears when using the LSS null hypothesis, as it appears clearly in Fig. 2, where we plot the function $P(\delta) \times [1 - P(\delta)]$ for the same cases of Fig. 1. This function vanishes if any of P or $1-P$ vanishes and has the theorethical maximum value of $1/4$. Thus, the higher its value is the more consistent the data are with the underlying hypothesis. Apart from the very small scales, where our results are unrealistic since we did not include magnetic smearing or detector angular resolution, the better concordance of the UHECR distribution with the LSS distribution than with the uniform one is evident at any scale. Taken at face value, our result implies a nominal probability $P \gtrsim 5\%$ that the main signature found in Ref. [1] arises as a chance fluctuation from the LSS distribution. This suggests that the clustering properties of LSS are in much better agreement with the experimental data than a pure isotropic distribution. This is not an unexpected feature given that, as found in [5], the typical size on the sky of the clusters of structures lies in the range 15°-30°.

A smoking gun in favor of the LSS-distribution would be a correlation between the data and the expected excess in the LSS map. By performing an analysis similar to the previous one, but in terms of the cross-correlation function between simulated data and sampled ones, we did not find any evidence favoring a LSS origin with respect to the uniform case. Actually this is not unexpected within the model considered in [5], since ~ 100 data at energy $\gtrsim 4 \times 10^{19}$ eV is still a too low statistics to draw a firm conclusion in this sense. However, the lack of this signature may also be related to the role of intervening magnetic fields. Acting on an

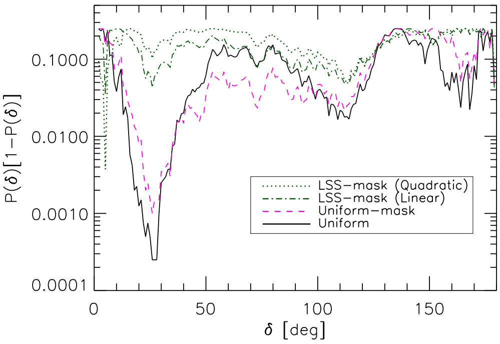

Figure 2: The function $P(\delta) \times [1 - P(\delta)]$ for the same cases shown in Fig. 1.

energetically (and possibly chemically) inhomogeneous sample, magnetic fields may displace the observed positions with respect to the original ones in a non trivial way, without evidence for a characteristic scale, at least in a poor statistics regime. A possible hint towards a non-negligible role of magnetic fields is given also by the fact that the dip in the LSS signal (but *not* in the UHECR one) is already present at relatively small angles. This feature may have disappeared in the UHECR sample due to a smearing effect of the magnetic fields.

3. Conclusions

Anisotropies are an important tool to distinguish between different origin and primary models for the UHECRs, nicely complementing the information on the energy spectrum and chemical composition. We have briefly summarized several signatures which one expects to show up in the pattern of UHECR arrival directions at different energies. In particular, we have analyzed the hypothesis that the broad maximum of the two-point autocorrelation function of the UHECRs arrival directions around 25° found in Ref. [1] may be due to the imprint of the LSS. We found that this result is indeed inconsistent with a purely isotropic sky, but consistent within 2 σ with the expectations for UHECRs tracing the LSS. A more-than-linear bias with overdensity improves the agreement. The still low statistics and the role of the magnetic field deflections may explain why no significant *cross-correlation* between data and LSS overdensities is found. Definitely, the larger statistics that the Auger Observatory will collect in the next years is needed to tell us finally if astronomy is possible with UHECRs or, equivalently, if we will be ever able to look at the sky with new and "ultra-energetic" eyes.

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